TELKOMNIKA, Vol.11, No.1, January 2013, pp. 28~39
ISSN: 2302-4046

Performance Analysis and Experimental Study on Flat Optical Comb Generation

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Abstract

The performance of the optical frequency comb generation based on the re-circulating frequency shifter has been analyzed and demonstrated in this paper. We have theoretically analyzed the condition for flatness of the optical frequency comb and the relative intensity noise influence. We find out the influence to the flatness of optical comb owing to amplifier relative intensity noise and modulator relative factors imperfect, such as input RF signals amplitude and phase deviation and modulator defect owing to manufacture for the first time. Moreover, to verify the theoretical analysis, a 16 comb lines and spacing 12.5 GHz RFS generation system have also been carried out, and the results are in good agreement with the theoretical analysis results.

Keywords: *Optical Frequency Comb; Modulation; Amplifier Noise; SNR*

1. Introduction

In recent years, optical frequency comb generation is attractive for many fields in optical communications such as optical arbitrary waveform generation, wavelength multiplexing, radio over fiber system and so on. Especially optical frequency comb generation is attractive for all-optical OFDM [1-4].

Conventional methods of optical frequency comb generation utilizing mode- locked lasers have been extensively studied for a long time, but it is extremely difficult to make a stable mode locking [5]. Many new methods have been proposed, but they cannot meet the requirements on high stability, flatness and low driving condition [6-10]. The optical comb generation using conventional Mach-Zehnder modulator [6] has been reported, but it cannot be operated in the theoretical optimal condition owing to its high driving voltage requirement,

Flat and stable optical comb generation based on RFS has been proposed [1]. Although they do really perfect work on experiments and theories, however, the performance analysis of flat and stable optical comb generation based on RFS is not complete also seriously have not been reported [11-13]. The latest experiments and theories results [12] for flat and stable optical comb generation based on the re-circulating frequency shifter which just demonstrates the input RF signals amplitude and phase deviation and modulator defect owing to manufacture to affect the modulator single-side band modulation output, not the flatness of the whole optical frequency comb lines. From the perspective of experiment results, it is vital of importance to get acquit on how sensitive the system performance can be when parameters varied from the idea operation points. So only the consideration on the single-side band modulator modulation output is not necessary and accuracy at all.

Therefore in this letter, we make a complete analysis of flat and stable optical comb generation based on the re-circulating frequency shifter. We have theoretically analyzed the condition for flatness of the optical frequency comb and the relative noise influence. We find out the influence to the flatness of optical comb owing to modulator relative factors imperfect for the first time, such as input RF signals amplitude and phase deviation and modulator defect owing to manufacture. Moreover, to verify the theoretical analysis, a 16 comb lines and spacing 12.5 GHz RFS generation system have also been carried out, and the results are in good agreement with the theoretical analysis results.

Received July 17, 2012; Revised November 20, 2012; Accepted November 27, 2012

2. Theoretical analysis of flat optical frequency comb generation

The configuration of optical frequency comb generator based on a re-circulating frequency shifter is illustrated in figure.1 (($E_{out-n}(t)$ -the output electrical field of the loop after the n-th circulation; $E_{out-3dB-n}(t)$ -the output electrical field of the loop at the 3-dB coupler after n-th circulation).

The re-circulating frequency shifter consists of an external cavity laser (ECL) whose line-width is small enough and an optical loop which comprises 3-dB coupler, IQ modulator, semiconductor optical amplifier (SOA), optical filter, tunable optical delay line and polarization controller (PC).

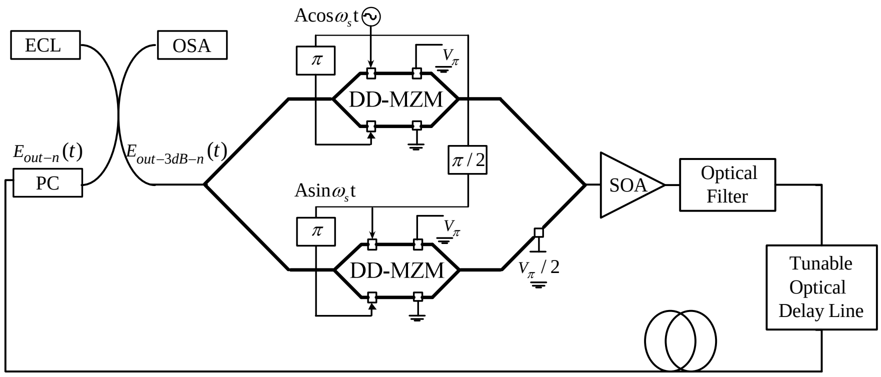

Figure 1. Optical frequency comb generation using re-circulating frequency shifter

The external cavity laser operating at 193.1-THz performs as a seed light source. The IQ modulator is configured for the operation in optical single side-band mode with carrier suppressed which shifts the optical carrier frequency up or down by the RF modulation frequency. In the re-circulating loop, this process of up- or down-shift conversion is going on, generating a new side-band line in each time of circulation and terminated when the newly converted comb line is across the pass-band edge of the optical filter. Therefore, the bandwidth of the optical filter determines the number of comb lines generated in the re-circulating frequency shifter.

The 3-dB coupler combines the seed light and the generated frequency comb lines to inject into the re-circulating loop.

The SOA is used for amplification of the optical signal to compensate for the insertion loss of the loop, which is dominated by the IQ modulator. Instead of EDFA usually used in optical communication systems, SOA is used for amplification in our methods. Because if stable and flat frequency comb lines is needed, a stable operation environment of the frequency comb generation is vital of importance. Otherwise, the fluctuating temperature will cause the random change of loop delay, bringing an additional phase noise to the comb line. Owing to the smaller package of SOA we can integrate the whole system into a temperature -stabilized environment to make the frequency comb lines stable.

The tunable optical delay line is inserted into the loop for meeting the optical phase condition which will be explained later.

In the beginning, there is no optical signal in the re-circulating frequency shifter, and the electrical field injected by the seed laser via the 3-dB coupler is given by:

$$E_{out-3dB-1}(t) = E_c e^{j[\omega_c t+\phi(t)]} \frac{1}{\sqrt{2}} j \quad (1)$$

where ω_c is the optical carrier angular frequency and $\phi(t)$ is the phase noise of the laser. Then this electrical field is modulated in the IQ modulator whose parameters comply with a reference paper[7]. Then the modulated electrical field is amplified by the SOA and looped back as:

$$E_{out-1}(t) = E_c e^{j[\omega_c(t-\tau)+\phi(t-\tau)]} \frac{1}{\sqrt{2}} j[(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s(t-\tau)}] * h(t-\tau) \quad (2)$$

where, τ is the time delay induced by the optical loop; G_{ss} denotes the SOA power gain; L is the loop power loss, including the insertion loss of 3dB coupler, IQ modulator, optical filter, optical delay line and optical fiber; $\omega_s = 2\pi f_s$, f_s is the frequency of RF modulation signal applied to the IQ modulator, also the comb spacing; β is the phase modulation index of IQ modulator, defined as $\pi A / V_\pi$ where V_π is the half-wave voltage of IQ modulator and A is the amplitude of RF modulation signal; $J_{-1}(\beta)$ denotes the -1-th order Bessel function; $h(t)$ is the impulse response of the optical filter whose Fourier transformation is the transfer function normalized to:

$$H(\omega) = \begin{cases} 1 & \omega_c < \omega \le \omega_c - N\omega_s \\ 0 & \omega = others \end{cases} \quad (3)$$

where N depends on the number of the comb lines we want to generate. N is taken to be 15 for total 16 comb lines, and the other one is the comb line formed by the injection of the seed laser. This means that the optical filter bandwidth should accommodate these comb lines to pass by.

At the beginning of the second circulation, the output electrical field modulated in the first circulation and the electrical field injected by the seed laser via the 3-dB coupler is given by:

$$E_{out-3dB-2}(t) = E_c e^{j[\omega_c t+\phi(t)]} \frac{1}{\sqrt{2}} j + \{E_c e^{j[\omega_c(t-\tau)+\phi(t-\tau)]} \frac{1}{\sqrt{2}} j[(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s(t-\tau)}] * h(t-\tau)\} \frac{1}{\sqrt{2}} \quad (4)$$

After the modulation in the loop, the modulated electrical field is amplified by the SOA and looped back as:

$$\begin{aligned} E_{out-2}(t) &= jE_c\{e^{j[\omega_c(t-\tau)+\phi(t-\tau)]} \frac{1}{\sqrt{2}}[(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s(t-\tau)}] * h(t-\tau) \\ &+ e^{j[\omega_c(t-2\tau)+\phi(t-2\tau)]} \frac{1}{\sqrt{2}}[(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s(t-2\tau)}] * h(t-2\tau)[(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s(t-\tau)}] * h(t-\tau)\} \frac{1}{\sqrt{2}} \\ &= jE_c e^{j\omega_c t} \sum_{n=1}^{2} \{e^{j[-n\omega_c\tau + \frac{n(n+1)}{2}\omega_s\tau]} e^{j\phi(t-n\tau)} [\frac{1}{\sqrt{2}}(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s t}]^n * h(t-\tau) * \cdots * h(t-n\tau)\} \end{aligned} \quad (5)$$

After the N -th circulation in the optical loop, the final output is expressed as:

$$\begin{aligned} E_{out-N}(t) = jE_c e^{j\omega_c t} \sum_{n=1}^{N} \{e^{j[-n\omega_c\tau + \frac{n(n+1)}{2}\omega_s\tau]} e^{j\phi(t-n\tau)} \times \\ [\frac{1}{\sqrt{2}}(-j)\sqrt{G_{ss}L} J_{-1}(\beta) e^{-j\omega_s t}]^n * h(t-\tau) * \cdots * h(t-n\tau)\} \end{aligned} \quad (6)$$

Meanwhile, the optical spectrum analyzer (OSA) at the output of 3 dB coupler will display the spectrum as:

$$E_{out-OSA}(t) = \frac{\sqrt{2}}{2}E_c e^{j[\omega_c t+\phi(t)]} - \frac{\sqrt{2}}{2}E_c e^{j\omega_c t}\sum_{n=1}^{N}\{e^{j[-n\omega_c\tau+\frac{n(n+1)}{2}\omega_s\tau]}e^{j\phi(t-n\tau)} \\ [\frac{\sqrt{2}}{2}(-j)\sqrt{G_{ss}L}J_{-1}(\beta)e^{-j\omega_s t}]^n * h(t-\tau)*\cdots*h(t-n\tau)\} \quad (7)$$

Assume that $\omega_c\tau = 2k\pi, \omega\tau = 2m\pi,$ where k, m are integers, then (7) is simplified to

$$E_{out-OSA}(t) = \frac{\sqrt{2}}{2}E_c e^{j[\omega_c t+\phi(t)]} - \frac{\sqrt{2}}{2}E_c\sum_{n=1}^{N}\{e^{j[(\omega_c-n\omega_s)t+j\phi(t-n\tau)]} \\ [\frac{\sqrt{2}}{2}(-j)\sqrt{G_{ss}L}J_{-1}(\beta)]^n\} \quad (8)$$

Obviously, the k-th comb line's frequency is $f_c - kf_s$ and its amplitude is

$$E_k = \frac{\sqrt{2}}{2}E_c[\frac{\sqrt{2}}{2}(-j)\sqrt{G_{ss}L}J_{-1}(\beta)L]^k \quad (9)$$

The k-th comb line's power is proportional to:

$$\left|E_k\right|^2 = \frac{1}{2}E_c^2G_{ss}^kL^kJ_{-1}^{2k}(\beta)(\frac{1}{\sqrt{2}})^{2k} \quad (10)$$

This expression indicates that if a flat spectrum of generated comb lines is required, the intensity of each line should be independent of k. This is true, if and only if the following condition is satisfied:

$$G_{ss}LJ_{-1}^2(\beta) = 2 \quad (11)$$

It is found that the flatness of the comb lines has no relation with the comb line spacing. Hence this approach is applicable in the future system for multi-wavelength source generation and super-high speed optical OFDM transmission.

If the condition $\omega_c\tau = 2k\pi, \omega\tau = 2m\pi$ is not kept, then each comb line generated will have a phase varying with time in step of τ . This additional phase modulation to the comb line causes side-bands which will be converted into intensity variation when the comb line as a light source transmits signal over a dispersive fiber link. To meet this phase condition, a tunable optical delay line is necessary. But the fiber loop delay time τ is temperature-dependent; therefore a temperature stabilization apparatus is needed for the re-circulating frequency shifter.

3. Theoretical analysis of system performance

The advantage of this optical modulation method based on a re-circulating frequency shifter is capable of generating a stable and ultra-flat optical comb. But even the condition (11) has been met, the flatness of the optical frequency comb is still impaired by the amplified spontaneous emission noise.

As shown in figure.1, let $n_{l-n}(t)$ to be the output noise after n times of loopback; $n_{l-3dB-n}(t)$ be the output noise at the 3-dB coupler after n times of loopback; $n_a(t)$ be the noise of optical amplifier which is added to the loop in re-circulating frequency shifter. $n_a(t)$ is assumed to be a white noise whose auto- correlation function is satisfied as $\left\langle n_a(t)n_a^*(t+\tau)\right\rangle = \frac{N_0}{2}\delta(\tau)$.

At the beginning, the optical amplifier noise is not modulated in the loop, consequently the output of the noise is given by:

$$n_{l-1}(t) = n_a(t-\tau) * h(t-\tau) \tag{12}$$

At the second time, the output noise signal at the 3-dB coupler after the first circulation is given by:

$$n_{l-3dB-2}(t) = \frac{\sqrt{2}}{2} n_a(t-\tau) * h(t-\tau) \tag{13}$$

After the modulation in the loop, the modulated noise is amplified by the SOA and is combined with a new optical amplifier noise, which is given as:

$$\begin{aligned} n_{l-2}(t) &= \frac{\sqrt{2}}{2} n_a(t-2\tau)[\sqrt{G_{ss}L}(-j)J_{-1}(\beta)e^{-j\omega(t-\tau)}] * h(t-2\tau) * h(t-\tau) + n_a(t-\tau) * h(t-\tau) \\ &= \frac{\sqrt{2}}{2} n_a(t-2\tau)e^{j\omega\tau}[\sqrt{G_{ss}L}(-j)J_{-1}(\beta)e^{-j\omega t}] * h(t-2\tau) * h(t-\tau) + n_a(t-\tau) * h(t-\tau) \end{aligned} \tag{14}$$

After N times of circulation in the loop, the final noise output is expressed as:

$$n_{l-N}(t) = \sum_{n=0}^{N} e^{j\frac{n(n+1)}{2}\omega\tau} n_a[t-(n+1)\tau][\frac{\sqrt{2}}{2}\sqrt{G_{ss}L}(-j)J_{-1}(\beta)e^{-j\omega t}]^n * h(t-\tau)\cdots * h(t-(n+1)\tau \tag{15}$$

Therefore the output noise displayed on the optical spectrum analyzer (OSA) will be as:

$$n_{l-n-OSA}(t) = -\frac{\sqrt{2}}{2}\sum_{n=0}^{N} e^{j\frac{n(n+1)}{2}\omega\tau} n_a[t-(n+1)\tau][\frac{\sqrt{2}}{2}\sqrt{G_{ss}L}(-j)J_{-1}(\beta)e^{-j\omega t}]^n * h(t-\tau)\cdots * h(t-(n+1)\tau) \tag{16}$$

To calculate the spectrum of amplified spontaneous emission noise in the loop, a transmission model is shown in figure.2, where the amplified spontaneous emission noise output from the SOA is modeled as a white noise. The transfer function of band-pass filter is expressed in (3).

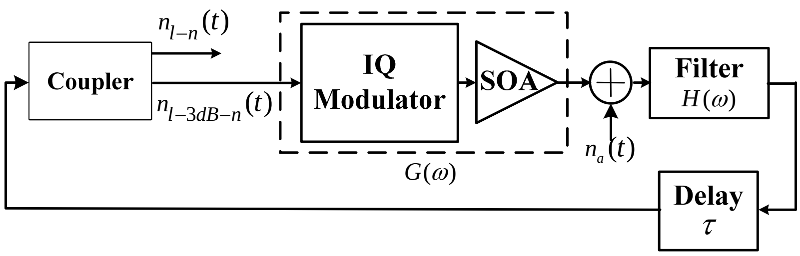

Figure 2. ASE noise analyses in Optical frequency comb generation.

The transfer function of IQ modulator and SOA combination is modeled as:

$$G(\omega) = \sqrt{G_{ss}L}J_{-1}(\beta)H(\omega - \omega_c + \omega_s) \tag{17}$$

where $\tilde{H}(\omega-\omega_c+\omega_s)$ is Hilbert transform centered at angular frequency $\omega_c-\omega_s$ which describes the SSB frequency down-shift characteristic of the IQ modulator.

Denote the electric field spectrum of $n_a(t)$, $n_{l-3dB-n}(t)$ and $n_{l-n}(t)$ as $S_n(\omega)$, $S_i(\omega)$ and $S_o(\omega)$ respectively, the noise transfer equation of RFS is as follows:

$$[S_i(\omega)G(\omega)+S_n(\omega)]H(\omega)e^{-j\omega\tau}\frac{1}{\sqrt{2}}=S_i(\omega)$$

$$\frac{S_o(\omega)}{S_n(\omega)}=j\frac{S_i(\omega)}{S_n(\omega)}=\frac{\frac{1}{\sqrt{2}}H(\omega)e^{-j(\omega\tau-\frac{\pi}{2})}}{1-\frac{1}{\sqrt{2}}G(\omega)H(\omega)e^{-j\omega\tau}}$$

$$=\frac{1}{\sqrt{2}}H(\omega)e^{-j(\omega\tau-\frac{\pi}{2})}\{1+[\frac{1}{\sqrt{2}}G(\omega)H(\omega)e^{-j\omega\tau}]+[\frac{1}{\sqrt{2}}G(\omega)H(\omega)e^{-j\omega\tau}]+\cdots\cdots$$

$$+[\frac{1}{\sqrt{2}}G(\omega)H(\omega)e^{-j\omega\tau}]^N+\cdots\cdots \tag{18}$$

The noise transfer function (19) includes a power series, which converge if $\left|\frac{1}{\sqrt{2}}G(\omega)H(\omega)\right|$ is slight less than 1.

Therefore, the condition of flat spectrum (11) should be corrected to satisfy that $G_{ss}LJ_{-1}^2(\beta)$ is slightly less than 2.

Because the power spectrum of $n_a(t)$ is $N_0/2$, the output noise power spectrum of the loop is: $\Phi_{l-n-\mathrm{OSA}}(\omega)=\frac{N_0}{2}\left|\frac{S_o(\omega)}{S_n(\omega)}\right|^2$

$\Phi_{l-n-\mathrm{OSA}}(\omega)$ can be expressed as:

$$\Phi_{l-n-OSA}(\omega)=\sum_{n=0}^{\infty}|N(\omega)|e^{j\phi_N(\omega)} \tag{19}$$

where $|N(\omega)|$ and $\phi_N(\omega)$ denote the magnitude and phase of noise spectrum. Because $G(\omega)$ is of step type and $H(\omega)$ is of square type, $|N(\omega)|$ is as:

$$|N(\omega)|=\begin{cases}\frac{N_0}{2},\omega_c-\omega_s\le\omega<\omega_c\\ \frac{N_0}{2}\times 2,\omega_c-2\omega_s\le\omega<\omega_c-\omega_s\\ \frac{N_0}{2}\times 3,\omega_c-3\omega_s\le\omega<\omega_c-2\omega_s\\ \cdots\\ \frac{N_0}{2}\times N,\omega_c-N\omega_s\le\omega<\omega_c-(N-1)\omega_s\end{cases} \tag{20}$$

From (20), we found that the noise background of RFS is stepwise like a ladder, i.e. the first optical frequency comb line suffers from the least influence of noise, meanwhile, the N-th comb line suffers from the most influence of noise, which is N times worse than that of the first comb line. Therefore the accumulated noise generated by the amplified spontaneous emission noise of SOA puts a limitation on the carrier-to-noise ratio of optical frequency comb lines and determines the total number of usable comb lines. An important task for the designer of optical frequency comb generator is to keep the noise enhancement in the loop as low as possible.

4. Numerical results of modulator factors influence on flat and stable optical comb

The IQ modulator is depicted as figure.1. There are three kinds of impact factors to the flatness of optical comb generator based on RFS. The impact factors shown in figure.3 are (1) DC bias deviation ΔV_P, ΔV_{bI}, ΔV_{bQ}; (2) RF signal amplitude variation ΔV_m and phase deviation θ; (3) modulator amplitude defect ΔV_I, ΔV_Q and phase defect $\Delta\varphi_I$, $\Delta\varphi_Q$, which are owing to manufacture. figure. 4~8 depicted the three kinds of impact factors to the flatness of optical comb generator based on RFS.

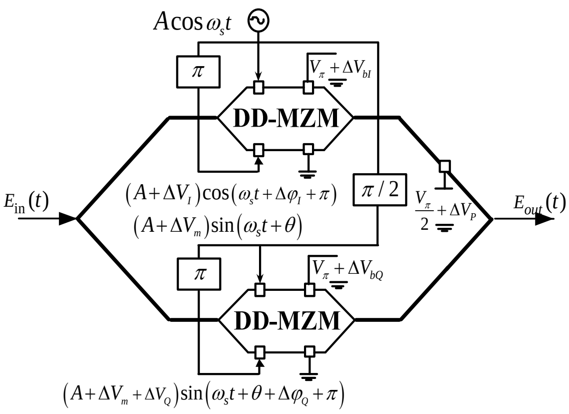

Figure 3. Types of modulator imperfect factors affecting the flatness of optical comb lines

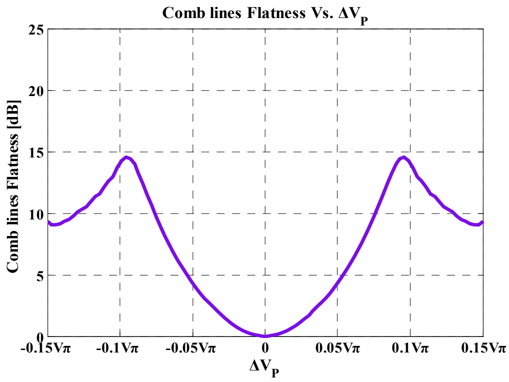

Figure 4. The impact of DC bias deviation ΔV_P on flatness of comb lines

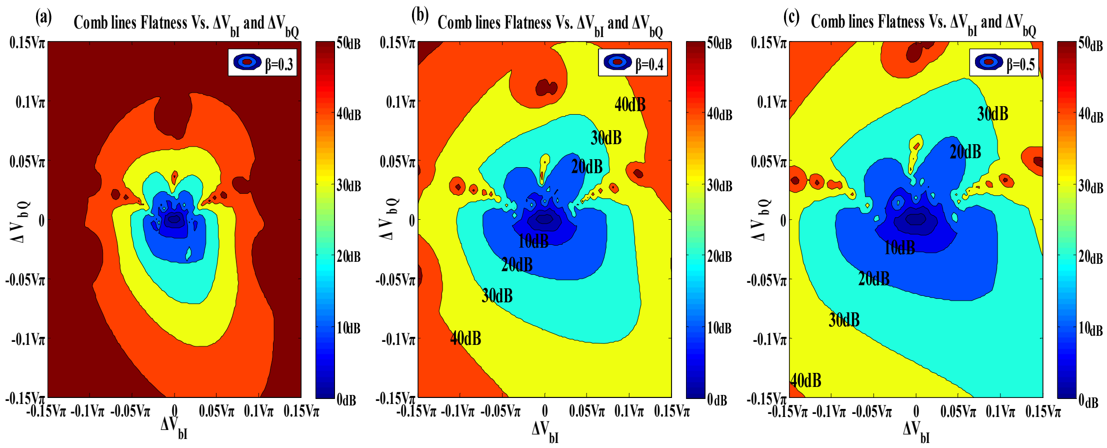

Figure 5. The impact of DC bias deviation ΔV_{bI} , ΔV_{bQ} on flatness of comb lines

(Where $\Delta\beta_I = \pi\frac{\Delta V_I}{V_\pi}$, $\Delta\beta_Q = \pi\frac{\Delta V_Q}{V_\pi}$) (a) β=0.3, (b) β=0.4, (c) β=0.5

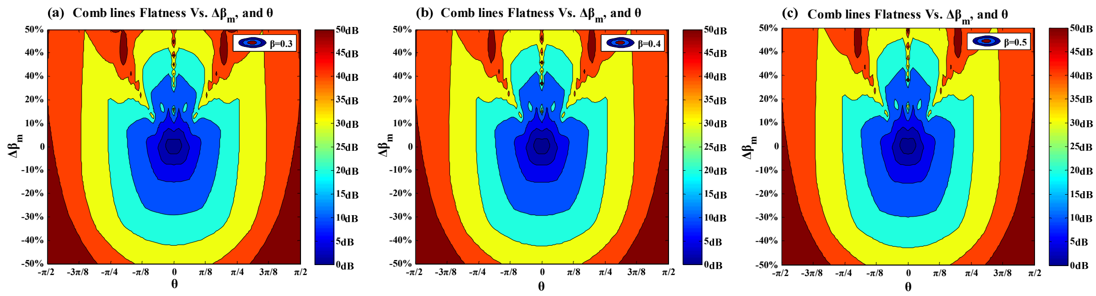

Figure 6. The impact of RF signals amplitude ΔV_m and phase θ deviation on flatness of comb lines (a) β=0.3, (b) β=0.4, (c) β=0.5

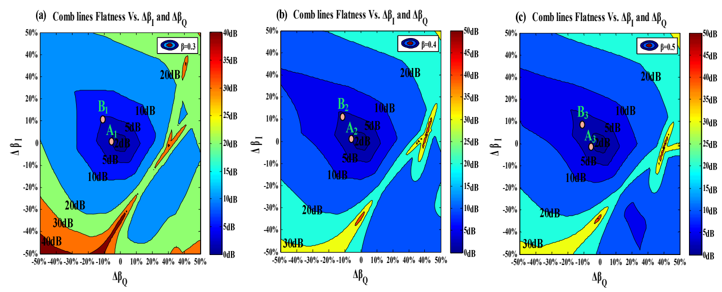

Figure 7. The impact of DC bias deviation ΔV_I , ΔV_Q on flatness of comb lines

(Where $\Delta\beta_I = \pi\dfrac{\Delta V_I}{V_\pi}$, $\Delta\beta_Q = \pi\dfrac{\Delta V_Q}{V_\pi}$) (a) β=0.3, (b) β=0.4, (c) β=0.5

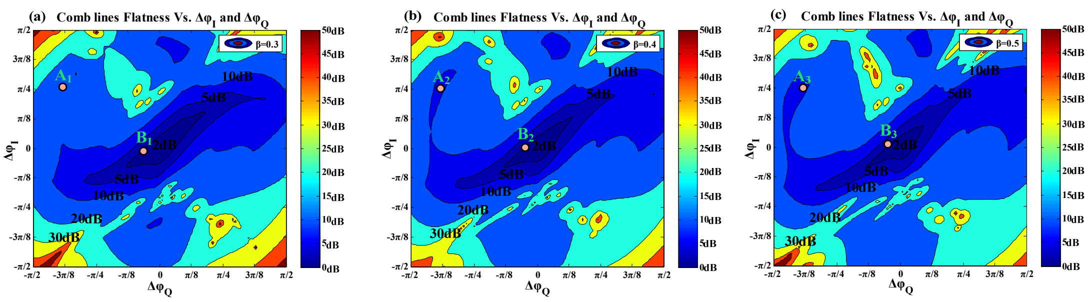

Figure 8. The impact of DC bias deviation $\Delta\varphi_I$, $\Delta\varphi_Q$ on flatness of comb lines (a) β=0.3, (b) β=0.4, (c) β=0.5

5. Experiment Results

In this section, we demonstrate an ultra-flat comb generator based on re-circulating frequency shifter to prove the described principle above. A 12.5-GHz spaced ultra-flat optical frequency comb generator is demonstrated.

The experimental setup for ultra-flat optical frequency comb generation using a re-circulating frequency shifter is according to figure.1. The external cavity laser (ECL) is RIO ORIONTM laser module 800676 whose emission frequency is 193.1-THz. The output power and the linewidth of ECL are -7dBm and 8.1kHz respectively. The IQ modulator is Covega dual-parallel modulator PN 10060 which is driven by Agilent E8257D PSG analog signal generator to generate a sine RF signal and a cosine RF signal at frequency 12.5-GHz. The bandwidth of Santec optical tunable filter OTF-350 is 200-GHz centered at 193.07-THz which ensures the generation of 16 comb lines. The saturated power of CIP SOA-L-OEC-1550 is 16dBm. The polarization controller is General Phonics polaRITETM. The optical spectrum obtained from the optical frequency comb generator is measured with Yokogawa optical spectrum analyzer AQ6370B. Because the optical spectrum analyzer is located after the 3-dB PM coupler, it displays the generated 15 optical frequency comb lines and the seed light, i.e. 16 comb lines in total.

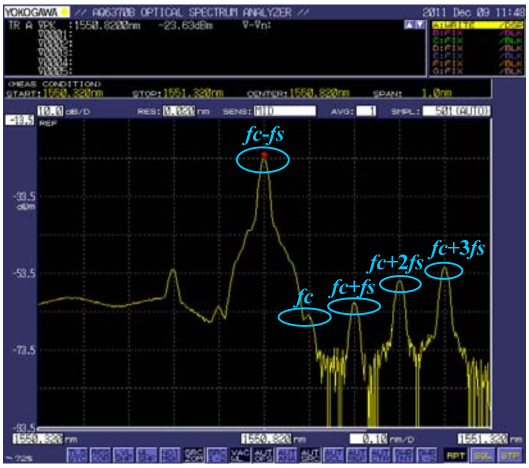

Figure 9. Optical spectrum of SSB modulation produced the IQ modulator

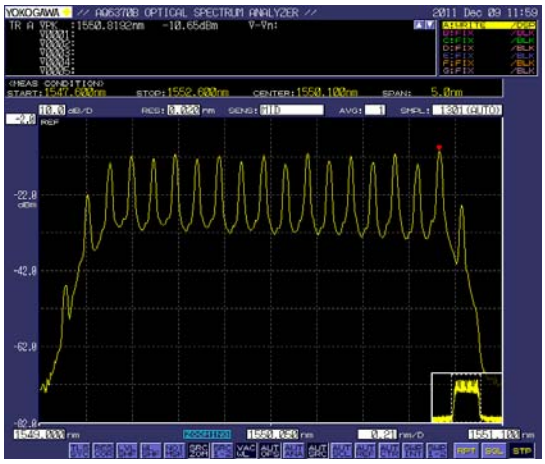

Figure 10. Optical spectra of comb lines

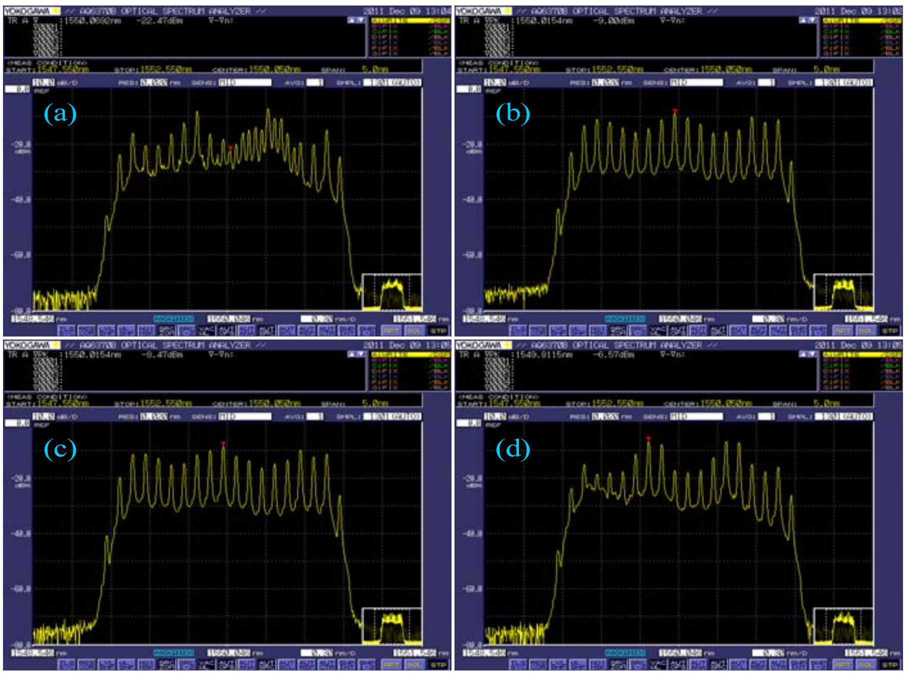

Figure 11. The output spectrum with $\Delta V_{bI} =$ (a) -2V; (b) -1V; (c) 1V (d) 2V

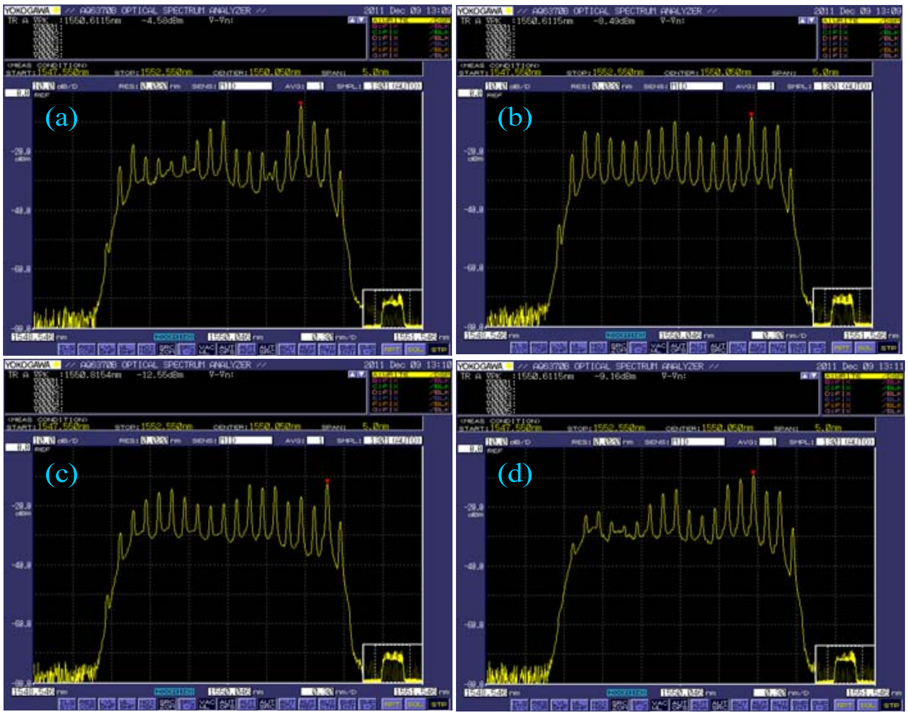

Figure12. The output spectrum with $\Delta V_{bQ} =$ (a) -2V; (b) -1V; (c) 1V (d) 2V

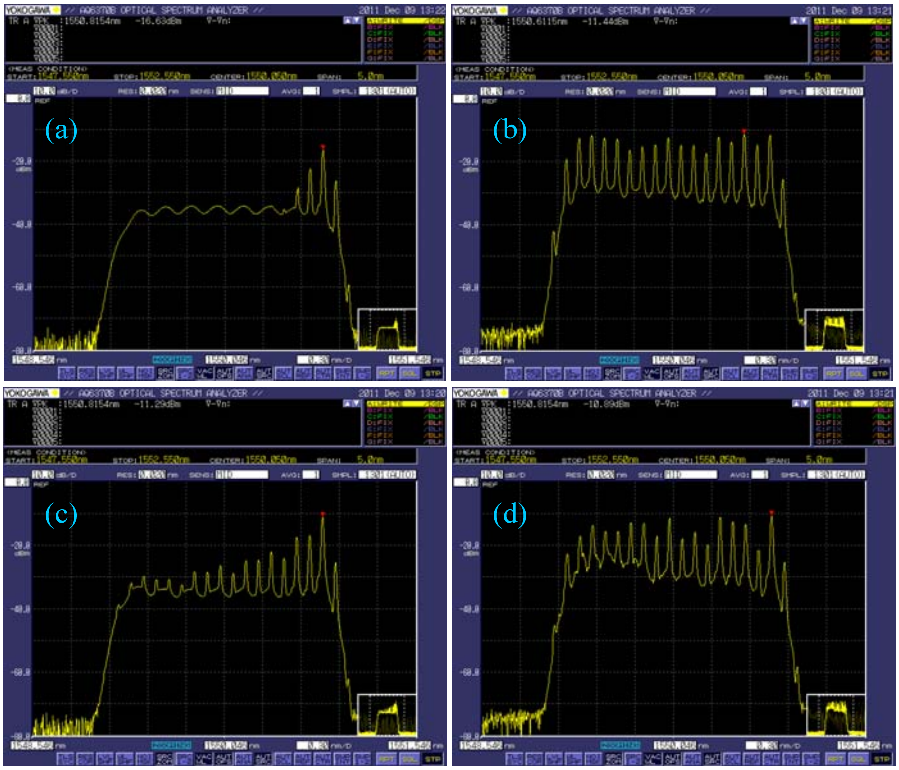

Figure13. The output spectrum with $\Delta V_p =$ (a) -2V; (b) -1V; (c) 1V (d) 2V

The performance of IQ modulator to output a single optical side-band signal is shown in Figure 9, where the higher order side-mode suppression ratio is almost 30 dB. This is an important figure for the comb line generation without residual mode interference.

The optimization condition of (11) is utilized. It means that the larger the -1-th order Bessel function the lower the SOA gain needed. After the optimal β is set up, the experiment result of 16 comb lines is demonstrated in figure.10 whose flatness is 2.8-dB and the effective OSNR of the last tone is around 20dB.We found that the flat comb lines are superimposed by the noise ladder step by step, and this phenomenon is in good accordance with the analysis we made. This experiment results in a stable and ultra-flat optical comb generated by the re-circulating frequency shifter method. The noise distribution on the comb lines should be considered in determination of the system SNR.

Then the impact of the deviation of DC bias is shown in Figures 11, 12, 13. As shown in Figure 11, when the ΔV_{bI} is -2V, -1V, 1V, 2V, the comb flatness is 15dB, 6dB, 7dB, 17dB respectively.

As shown in figure.12,as ΔV_{bQ} is -2V, -1V, 1V, 2V, the comb flatness is 19dB, 13dB, 16dB, 17dB ,respectively. Also as shown in figure.13,when the ΔV_p is -2V, -1V, 1V, 2V, the comb flatness is 18dB, 11dB, 7dB, 11dB, respectively. The above experimental result is in good agreement with the theoretical analysis.

6. Conclusions

The performance of the optical frequency comb generation based on the re-circulating frequency shifter has been theoretically analyzed and experimentally demonstrated. We have found the condition for flatness of the optical frequency comb and the influence to the flatness of optical comb owing to amplifier relative intensity noise and modulator relative factors imperfect as well. Moreover, to verify the theoretical analysis, a 16 comb lines and spacing 12.5 GHz RFS generation system have also been carried out, and the results are in good agreement with the theoretical analysis results. These results lay a solid basis for establishing an actual optical comb generator useful for super-high capacity optical communication systems.

7. Acknowledgement

This work is supported by the Foundation of Shanghai Scientific and Technological Development (Project No.11511502500, No.11510500500, No.11CXY33) and National Natural Science Foundation of China (No.61132004, No.61275073), Shanghai Leading Academic Discipline (No.S30108).

References

[1] Y Ma, Q Yang, Y Tang, S Chen, and W Shieh. "1-Tb/s single-channel coherent optical OFDM transmission over 600-km SSMF fiber with subwavelength bandwidth access," *Opt. Express,* 2009; 17(11): 9421–9427.

[2] J Yu, Z Dong, and N Chi. "1.96-Tb/s (21x100 Gb/s) optical OFDM superchannel generation and transmission over 3200-km SMF-28 with EDFA-only". *IEEE Photon. Technol. Lett*. 2011; 23: 1061–1063.

[3] Chandrasekhar, S Xiang Liu, Zhu, B Peckham, DW. "Transmission of a 1.2-Tb/s 24-Carrier No-Guard-Interval Coherent OFDM Superchannel over 7200-km of Ultra-Large-Area Fiber", *ECOC,* 2009.

[4] B Zhu, X Liu, S Chandrasekhar, D Peckham, and R Lingle. "Ultra-long-haul transmission of 1.2-Tb/s multicarrier no-guard-interval CO-OFDM superchannel using ultra-large-area fiber". *IEEE Photon. Technol. Lett*. 2010; 22(11): 826–828.

[5] M Hirano, T Wada and A Morimoto, "Wide-band Flat Optical Comb Generation Using Fiber Loop Modulation and Injection Locking," *Lasers & Electro optics & Electro-optics Conference*, 2009: 1-2.

[6] Sakamoto T, Kawanishi T, and Izulsu M. "Optimization of Electro-Optic Comb Generation Using Conventional Mach-Zehnder Modulator," *Microwave Photonics*, 2007: 50-53.

[7] Michiyuki Endo and Hidemi Tsuchida, "Investigation of single sideband optical frequency comb generations using a dual-electrode Mach-Zehnder modulator in a fiber recirculating loop," *Lasers and Electro- Optics*, 1999; 3: 771-772.

[8] Keang-Po Ho and Joseph M Kahn. "Optical Frequency Comb Generator Using Phase Modulation in Amplified Circulating Loop," *IEEE Photon. Technol. Lett*. 1993; 5(6): 721-725,.

[9] S Ozharar, F Quinlan, I Ozdur, S Gee, and PJ Delfyett. "Ultraflat Optical Comb Generation by Phase-Only Modulation of Continuous-Wave Light," *IEEE Photon. Technol. Lett*., 2008; 20(1): 36-38.

[10] S Oikawa, T Saitou, N Mitsugi, K Kubodera, T Kawanishi, and M. Izutsu. "Single Side-Band Modulation Performance of a LiNbO3 Integrated Modulator Consisting of Four-Phase Modulator Waveguides". *IEEE Photon. Technol. Lett.*, 2001; 13(4): 364-366,.

[11] Jianping Li, Xuan Li, Xiaoguang Zhang, Feng Tian and Lixia Xi. "Analysis of the stability and optimizing operation of the single-side-band modulator based on re-circulating frequency shifter used for the T-bit/s optical communication transmission". *Optics Express*. 2010; 18(17): 17597-17609.

[12] Jiaping Li, Xiaoguang Zhang, Feng Tian and Lixia Xi. "Theoretical and experimental study on generation of stable and high-quality multi-carrier source based on re-circulating frequency shifter used for Tb/s optical transmission". *Optics Express*. 2011; 19(2): 848-860.

[13] Lin Zhang, Yingxiong Song, Shihuan Zou, Yingchun Li, Jiajun Ye, Rujian Lin. "Performance Analysis of Flat and stable optical comb Generation Based on Re-circulating Frequency Shifter", *International Conference on Applications of Optics and Photonics*. Portugal. 2011.